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EXPERIMENT STUDY ON SURFACE INTEGRITY IN END MILLING OF HASTELLOY C-2000 SUPERALLOY

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ABSTRACT

This paper presents an experimental study of surface integrity in end milling of Hastelloy C-2000. The experiment was carried out using two different cutting inserts under wet conditions – namely Physical Vapor Deposition (PVD) coated carbide with TiAlN and uncoated carbide. Design of experiment (DOE) was implemented with Box-Behnken design. The surface integrity of workpiece was analyzed through scanning electron microscope (SEM) and chemical element changes were inspected by energy dispersive X-ray (EDX) test. The surface integrity of Hastelloy C-2000 was better when machining with coated carbide compare to uncoated carbide cutting insert mainly due to coating layer of coated carbide which acted as protecting layer to the cutting tool insert. Surface defects such as feed marks, surface tearing, plucking, cracking and adhered chips were found during machining process. The chemical element changes happened due to the adhesion and diffusion mechanism which were identify using SEM and EDX.

Keywords: Nickel based superalloy; coated carbide; end mill; uncoated carbide; adhesion wear; diffusion wear.

INTRODUCTION

Hastelloy C-2000 is a nickel-chromium-molybdenum (Ni-Cr-Mo) C-type alloy which is used in the aerospace, marine and food processing, chemical process industries (Razak et al., 2012). The alloy can contain carbides and abrasive particles that can create high tool wear. According to Shokrani et al. (2012), difficulties as well as high costs were expected in machining of this alloy because it was designed to retain its strength at elevated temperatures. Thus, great efforts were being made to find an economical method of machining these alloys to enhance its performance. The condition of a machined surface may be innate or else it acquired surface integrity analysis by mechanical, metallurgical, chemical and topological state of the surface. Changes in corrosion resistance, hardness variation, surface roughness, residual stress, etc. then used to measure these states. The surface integrity is given so much attention during machining (Ulutan and Ozel, 2011). The reported thermal and mechanical cycling, microstructural transformations, and mechanical and thermal deformations during of machining processes caused these impacts (Axinte and Dewes, 2002). In the case where the fatigue life of a machined part is deemed central, the smoothest possible surface was important (Novovic et al., 2004). A greater strength of nickel based alloys was due to elevated temperature, high ductility and high tendency to work hardening. Thus, the heat treatment strengthened the superalloys because of their sensitivity to microstructure change (Dudzinski et al., 2004). Another factor that can be essentially critical to the machined surfaces is the shape of the cutting tool. By feeding in a machine with round shape cutting insert the surface finish and minimum surface damage can be rectified. The hardness of the surface layer and the machined surfaces are inversely proportional when exposed to extend machining. The reason for this is a high flank wear. As a result the component forces and cutting temperature increases because of higher contact area and relation motion between the flank land of the tool nose region and the freshly machined surface of the workpiece (Che Haron et al., 2007). The residual stresses, chemical change between the work piece and tool materials, micro cracking, tears, plastic deformation, metallurgical transformations and changes in hardness of the surface layer declared as the foremost changes in the machined surface layer. This paper presents the surface integrity of end milled characterization of Hastelloy C-2000.

METHODS AND MATERIALS

Design Of Experiments

Design of experiments (DOE) used to reduce the number of experiments and time consumption. The study uses the Box-Behnken design because it has fewer design points and less expensive to run than central composite designs with the same number of factors. The Box-Behnken design was used to optimize the experiment of judging effects of important parameters by using response surface method (RSM) (Khan et al., 2011; Zhao et al., 2006; Rahman et al., 2010, 2011a,b,c). Three levels of cutting parameters were selected to investigate the machinability of this alloy as shown in Table 1. The parameter inputs were recommended by Table 2 shows parameter settings in the DOE.

Table 1. Machining parameters and their levels.

Process Parameters	Level		
	-1	0	1
Feed rate (mm/tooth)	0.1	0.15	0.2
Axial depth (mm)	0.4	0.7	1
Cutting speed (mm/min)	15	23	31

Experimental Details

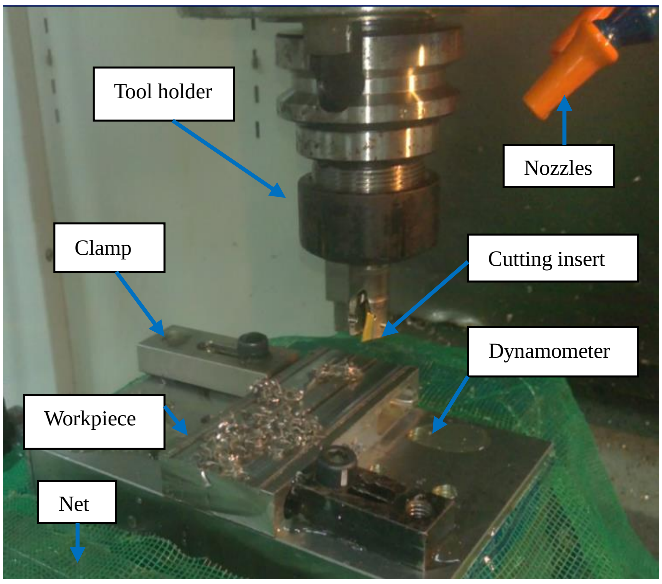
Surface of Hastelloy C-2000 blocks of 46 mm × 120 mm × 20 mm dimensions were prepared using moist cloth and sand paper. As the sticking dust makes the block very rough, so it is very beneficial to clean it before processing further. The top surface is machined from the block. A dynamometer is attached to the slot and was clamped to the block. A wet cutting condition was conducted to test the effectiveness of HAAS TM-2 CNC milling machine. The machine was equipped with 5.6 KW motor drive, 400 rpm spindle speed and 5.1 m/min feed rate. The coated carbide (CTW 4615) and uncoated carbide (CTP 1235) were used in the cutting tool. For each 15 different experiments, a new set of cutting tool was used every time to get authentic data. Along with the dynamometer, a workpiece block was fastened on the table of CNC milling. On the other side, a CNC program was applied to cut the block in 120 mm length.

Table 2. DOE of Hastlelloy C-2000.

Expt. No.	Feed rate (mm/tooth)	Axial Depth (mm)	Cutting speed (m/min)
1	0. 15	0.4	31
2	0.15	1	15
3	0.1	0.7	15
4	0.2	1	23
5	0.2	0.7	31
6	0.15	0.7	23
7	0.15	0.7	23
8	0.2	0.7	15
9	0.1	0.4	23
10	0.15	1	31
11	0.15	0.4	15
12	0.1	0.7	31
13	0.1	1	23
14	0.15	0.7	23
15	0.2	0.4	23

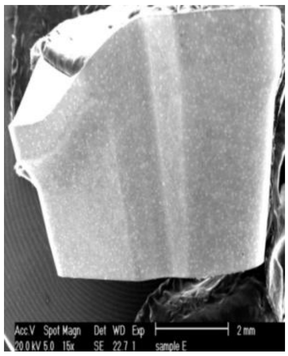
A portable roughness tester (MarSurf PS) was used to measure surface roughness of block. A Scanning Electron Microscope was used to analyze the integrity of the block surface. An advanced optical video computing system was used to evaluate the effectiveness of the cutting tool. The tool holder was removed from the panel of the testing machine, during measurement operation. Flank wear was tested by using it on cutting 120 mm long block. After the first half, the tool wear at the face of the flank was measured to get the accurate result. The frequency of the tool wear was depended upon the rate of growth when the wear. The actual life of the tool was calculated by the total time of the cutting the cutting-part to get a specific tool life. During the milling operation, the Kistler charge Amplifier model 5070 and Kistler dynamometer model 1679A5 were used to measure the cutting force. These tools save the data of the critical forces into the computer for future analysis. At the end of this experiment, the chips were examined to know the mechanism of them. The workpice was removed from the clamp and then undergone the grinding and polishing process before conducting the surface integrity of the workpiece by scanning electron microscope. A mixture of epoxy and hardener was poured in a little container of size 30 mm in diameter. Before the next stage, the specimens were kept to dry out and get hardened. Then with a Cameo Platinum with a wheeler having speed of 150 rpm was used to grind the fixed workpiece. The polishing starts with a Cameo silver disc of 6 micron having a speed of 150 rpm, then again a Cameo White FAS Disc of 3 micron with a diamond mixture, along with the diamond mixture of 1 micron and red cloth plus a micro extender of speed 200 rpm. Before the last process of giving the ultrasonic bath to get rid of the coolant and residue, polishing was done with colloidal silica of 0.05 micron along with imperial cloth and water having a wheeler speed of 150 rpm. The ultra sonic bath was given by Aqua Regia-Glycerol an etching compound, and before this specimen was cleaned with an ultrasonic cleaner. The chemical and physical properties of the workpiece material Hastelloy C-2000 are given in Table 3 and Table 4 respectively. The composition of the cutting insert shows in Table 5.

Figure 1 shows the shape of cutting insert. CTW 4615 is a coated carbide grade with TiAlN coating PVD with grade designation P35 M50. Titanium-aluminum nitride (TiA1N) is very effective in cutting stainless steels and aerospace alloys. The advantages of hard material layers consist in reduction of friction, heat, oxidation and diffusion CTP 1235 is uncoated carbide with grade designation K15. The following are the details of the tool geometry of inserts when mounted on the tool holder: (a) special shape ; (b) axial rake angle: 19.5°; (c) radial angle: 5°; and (d) sharp cutting edge. Fig. 1 shows the experimental set up and shape of uncoated carbide inserts (a) workpiece at CNC milling machine, (b) CNC milling machine, (c) shape of cutting insert, (d) SEM viewing of uncoated carbide before machining. Table 5 shows the composition of cutting inserts.



(a) Workpiece at CNC milling machine

(b) Shape of cutting insert



(c) SEM viewing

Figure 1. Experimental Set up

Table 3. Chemical composition (%) of material Hastelloy C-2000.

Ni	Cr	Mo	Fe	Cu	Al	Mn	Si	C
BAL	23	16	3	1.60	0.50	0.50	0.08	0.01

Table 4. Physical properties of workpiece material (Hastelloy C-2000 at room temperature).

Parameters and unit	Value
Density (g/cm^3)	8.5
Thermal conductivity (W/m°C)	9.1
Mean coefficient of thermal expansion (μm/m°C)	12.4
Thermal Diffusivity (cm^2/s)	0.025
Specific heat (J/kg°C)	428
Modulus of elasticity (GPa)	223

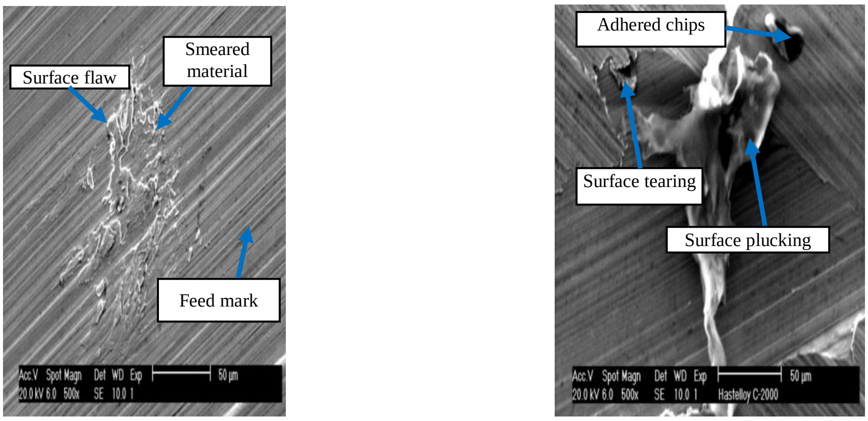
Table 5. The composition of the cutting inserts.

Code name	Composition	Coating	Grain size
CTW 4615	6% Co,4% carbide,90% WC	PVD-TiA1N,TiN	1μm
CTP 1235	6% Co, 94 % WC	-	4μm

RESULTS AND DISCUSSION

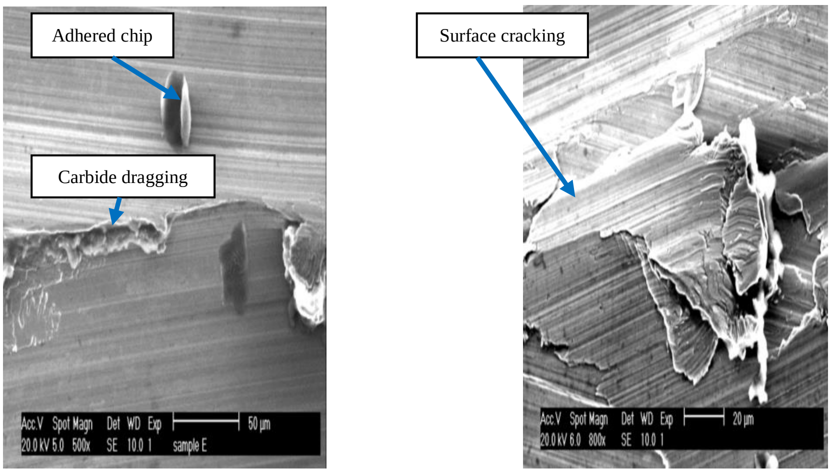
Micrographs of coated and uncoated carbide inserts can be observed in Figure 2 since it shows the images of scanning electron microscope (SEM). A feed rate of 0.2 mm/tooth, axial depth 0.7 mm and cutting speed 15 m/min has been used for the images that are taken and a surface defect has been found due to the low cutting speed. During the machining of the workpiece of the coated carbide cutting insert, there are several kinds of surface defects which occured. Out of these few the surface flaw, feed marks and chip redeposition were the most common kinds of defects that occur as shown in Figure 2(a). The severity of a feed mark can be changed by optimizing the feed rate or than varying it in order to carry out effective machining process (Ginting and Nouri, 2009). Furthermore, plucking of particles from the surface and their redeposition to the surface create two different defects. The particles have the ability to cause tearing and dragging effect on the surface of the next pass. In the case of uncoated carbide, the same kind of surface plucking and tearing would take place. The uncoated carbide has a very different surface texture from the coated carbide which is mainly because the coating layer helps make the tool harder and tougher with a good surface finish. The residual stress which is present on the surface machine is improved along with reducing the cutting temperature and enhancing of the machine surface with the help of the coating layer (Outeiro et al., 2008). It was observed that the compressive stresses increases when increase of the thermal softening of the material and such surface flaws clear out of the machined surface and enabling the workpiece near- surface to reconstruct itself easily (Pawade et al., 2007).

Prolonged machining tends to increase the hardness of surface layer and also deteriorates the surface finish of machined workpiece due to the fact that the contact area and motion that exists between the tool, flank area and workpiece machine surface is increased hence causing surface defect, increase component cutting forces and temperature and flank wear. With presence of nickel based alloys, many issues arise since the cutting parameters affect the defects to an extent. To avoid these problems the cutting condition optimization is essential. The machining processes have been observed to have many defects in the surface specifically in the micron precisions. It is unfeasible to entirely remove the cutting parameters or even adjust them to an extent. There are carbide particles in the structure of nickel based work piece materials along with coating inserts material with carbide particles. Detachment of the carbide particles with the machine surface or the tool inserts occurred when the work piece is machined or stuck on the work piece surface. Such process is referred to as carbide cracking and may cause an increase in the level of stress when the cutting takes place due to plucking in the surface cavities (Zou et al., 2009). Figure 3 shows the carbide cracking formation. Residual cavities and cracks occur in the machine surface which may cause several issues in terms of the micro-scale surface integrity. The chemical composition of the material when machining takes place of the coated and uncoated carbide tool inserts is shown in Table 4. Cobalt has been formed in the EDX test when checking the texture of the machined surface; hence proving that adhesion mechanism does take place as shown in Figure 4. This Cobalt, Co is a new element of the Hastelloy C-2000 which is present due to the high temperature of machining and the chemical change that takes place between the cutting tool insert and the work piece.



(a) Coated carbide (b) Uncoated carbide

Figure 2. SEM viewing of Hastelloy C-2000 texture at 500x.



(a) Magnification, 500x (b) Magnification, 800x

Figure 3. SEM viewing of experimental no 3 with two different magnifications for uncoated carbide insert.

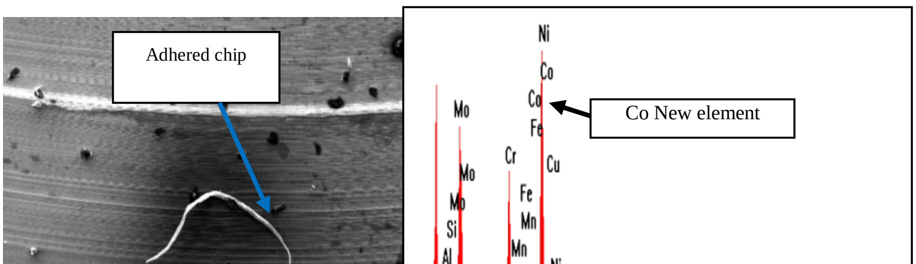


Figure 4. Adhesion and diffusion base on EDX result at magnification 100x at coated carbide inserts.

The formation of cobalt happened due to adhesive mechanism during machining where the coated carbide itself contains the component of cobalt. The rake face is protected with the help of the adhering element (Co) as it became a stable built-up-edge (Itakura et al., 1999). Diffusion took place where vast increase or decrease occurred in the elements of carbon (C), Aluminum (Al) and Molybdenum (Mo). Due to this mechanism, the atom present in the metallic crystal lattice changes from the higher atomic concentration to the lower concentration level. The case of diffusion also occurs when applying uncoated carbide, however, with no adhesion formation found as happened in coated carbide as shown in Figure 5. It take place during cutting condition of feed rate of 0.2 mm/tooth, axial depth 1.0 mm and cutting speed 23 m/min. Here, decrease is found in composition of chromium (Cr), manganese (Mn), copper (Cu), ferum (Fe) and Nickel (Ni) and an increase is observed in molybdenum (Mo), aluminum (Al), silicon (Si), and carbon. The changes of chemical composition when machining Hastelloy C-2000 with coated and uncoated carbide insert can be seen at Table 6.

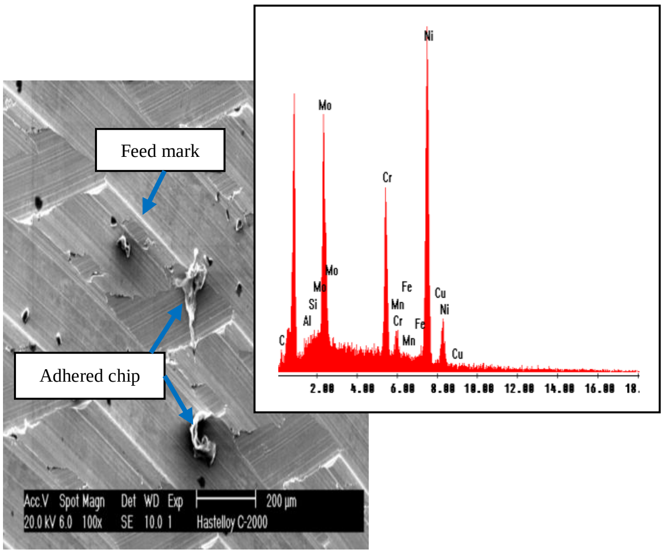


Figure 5. The diffusion based on EDX result at magnification 100x for uncoated carbide insert.

Table 6. Chemical composition (%) of material (Hastelloy C-2000), before and after machining for coated and uncoated carbide inserts

Components	Before machining	After machining	
		Coated carbide	Uncoated carbide
Ni	55.310	54.00	54.22
Cr	23.000	12.83	15.28
Mo	16.000	24.53	24.84
Fe	3.000	1.05	0.45
Cu	1.600	2.16	1.25
Al	0.500	1.20	0.58
Mn	0.500	0.57	0.29
Si	0.008	0.76	0.71
C	0.010	1.89	2.38
Co	-	1.01	-

CONCLUSIONS

The uncoated carbide has a very different surface texture from the coated carbide which is mainly because the coating layer helps make the tool harder and tougher with a better surface finish. The residual stress on the surface machine is improved along with reducing the cutting temperature and enhancing of the machine surface with the help of the coating layer. Prolonged machining tends to increase the hardness of surface layer and also deteriorates the surface finish of machined workpiece. The contact area and motion that exists between the tool, flank area and workpiece machine surface is increased hence causing surface defect, increase component cutting forces and temperature and flank wear. There are carbide particles in the structure of nickel based work piece materials along with coating inserts material with carbide particles.

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